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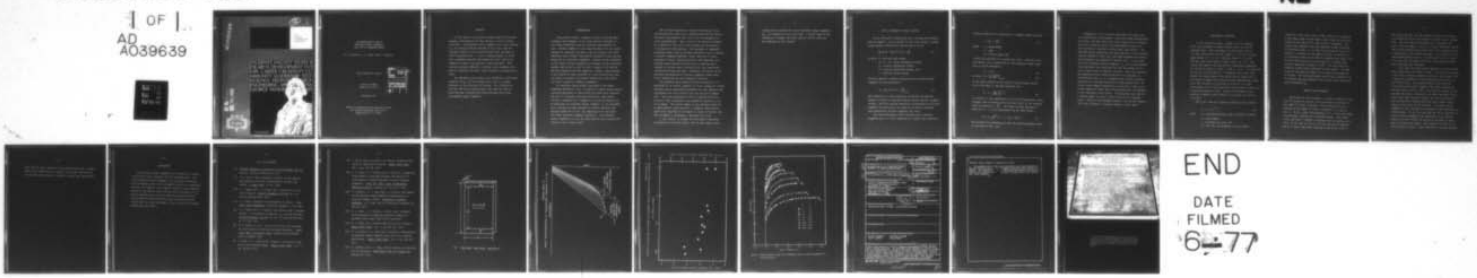

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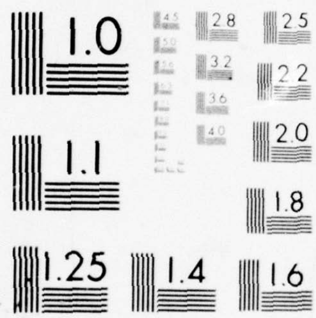

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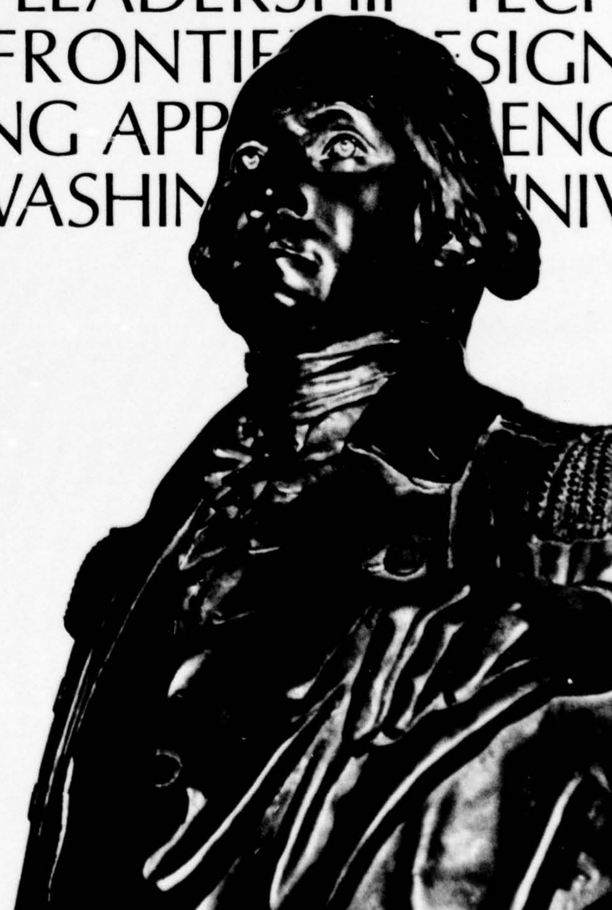

SCHOOL OF ENGINEERING
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DETERMINATION OF CYCLIC NONLINEAR ENERGY TOUGHNESS FOR 7075-T6 ALUMINUM SHEETS

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ABSTRACT

In this report, the nonlinear energy method for fracture toughness determination has been applied to cyclic loading conditions. The nonlinear energy toughness for cyclic loading, $\tilde{G}_{fc}$, was obtained from an envelope of the cyclic load-displacement record for thin center-cracked sheet specimens of 7075-T6 aluminum alloy. A cyclic loading program, in which each succeeding load peak approached the static load in an exponential manner, was applied to these specimens. With constant specimen dimensions, different load increments were used for different specimens, which resulted in varying cyclic lives.

The specimens used in these tests exhibited a significant reduction in $\tilde{G}_{fc}$ with increasing cyclic life in a manner analogous to the classical S-N diagram. This reduction in life for 7075-T6 was significantly less than for 2024-T3, which had been evaluated previously, although 2024-T3 has considerably higher toughness.

INTRODUCTION

Plane strain fracture toughness testing of the new high-strength, high-toughness alloys often requires specimens of very large thicknesses that are difficult and expensive to test. Further, members of such large thickness are not usually employed in structures and, hence, the test results with thick specimens yield a highly conservative estimate of load carrying capacities of structural components. Because of the inadequacy of the linear fracture toughness test method, several nonlinear methods such as the R curve [1] the J integral [2-4] and the COD [5,6] methods have been suggested. However, these methods do not provide an exact treatment of crack-tip plasticity and are unable to properly incorporate subcritical crack growth into their respective toughness parameters.

The nonlinear energy method, developed at The George Washington University [7,8], is based on a global energy balance criterion applicable to both brittle and semibrittle fracture, and also to situations involving subcritical crack growth. From this consideration a toughness criterion was defined and an expression for nonlinear energy toughness, $\tilde{G}_c$ was developed. This criterion has been examined for several materials and specimen geometries [9-11], and comparisons have been made with other nonlinear toughness parameters. The nonlinear energy toughness $\tilde{G}_c$ or $\tilde{G}_{Ic}$ has been found to give satisfactory results in all of these cases.

The classical approach to studying the behavior of un-notched materials under cyclic loading conditions has been to determine experimentally the cyclic life corresponding to a given load amplitude. Then, a plot of the material strength as a function of the cyclic life provides the conventional S-N diagram for that material. For specimens or components containing sharp cracks or notches subjected to cyclic loading, a fracture toughness approach, rather than the S-N curve, represents a better characterization of the remaining life. Although some attention has been given to applying the J integral to fatigue crack initiation [12], only theoretical considerations have been made. Therefore, the matter of the practical determination of fracture toughness values under cyclic loading has not been adequately addressed.

The nonlinear energy method has been examined for its applicability to certain sequences of cyclic loading of cracked specimens and an experimental procedure has been employed that incorporates the cyclic effects into the fracture toughness [13]. Thin sheet specimens of 2024-T3 aluminum alloy were tested at loads increasing as an exponential function of the cycle number. The limited number of data obtained exhibited an approximately linear decrease in toughness when plotted against the logarithm of the number of cycles to failure, and thus resembled in appearance a compressed S-N curve.

In this report, an attempt has been made to determine the behavior of the more brittle 7075-T6 alloy under cyclic

loading and to evaluate the cyclic nonlinear energy toughness, $\tilde{G}_{fc}$, as a function of the cyclic life. A larger range of the exponential increment than that used for 2024-T3 alloy has been employed in this program.

THE $\tilde{G}_c$ APPROACH TO CYCLIC LOADING

For an arbitrarily shaped body with a through-the-thickness crack of length c, at any instant of slow crack growth, a global energy balance criterion has been written as [7,8],

$$\frac{\partial}{\partial c}(W-U) = \frac{\partial}{\partial c}(W-U'-U'') = \frac{\partial \Gamma}{\partial c}\ , \tag{1}$$

in which W = external work energy,

U = U' + U" = total deformation energy,

U' = elastic deformation energy,

U" = plastic deformation energy, and

Γ = fracture surface energy.

From this equality a general definition for nonlinear energy toughness has been obtained as

$$\tilde{G}_c = \frac{\partial}{\partial c}(W-U'-U'') = \left.\frac{\partial \Gamma}{\partial c}\right|_{crit}\ . \tag{2}$$

This definition is valid regardless of whether the material exhibits a linear or nonlinear behavior during fracture toughness testing. From this general definition an expression for fracture toughness has been given [7], which can be easily evaluated from conventional fracture toughness test data.

The load-displacement record obtained from a fracture toughness test is a curve comprised of a linear and a nonlinear

portion, which can be represented by a Ramberg-Osgood relation

$$v = \frac{F}{M} + k\left(\frac{F}{M}\right)^n , \tag{3}$$

where v = displacement

F = load

M = initial slope, and

n and k are constants for a given test curve. From this relation and eq. (2) an expression for the nonlinear energy toughness $\tilde{G}_c$ can be obtained as

$$\tilde{G}_c = \tilde{C}\,\overline{G}_c , \tag{4}$$

in which $$\overline{G}_c = \frac{F^2}{2B}\left.\frac{\partial(1/M)}{\partial c}\right|_{crit} \tag{5}$$

is the linear portion of the critical strain energy release rate at the onset of unstable fracture, and

$$\tilde{C} = \left[1 + \frac{2nk}{n+1}\left(\frac{F}{M}\right)^{n-1}\right] \tag{6}$$

is a measure of the nonlinearity of the load-displacement record. Although other procedures could have been used, $\overline{G}_c$ was obtained from the relation $\overline{G}_c = \frac{K_c^2}{E}$. For center-cracked specimens as shown in Fig. 1, K_c was determined from the ASTM formula

$$K_c = \sigma_c\left(\frac{\pi c}{2}\right)^{\frac{1}{2}}\left[1 - 0.1\left(\frac{c}{w}\right) + \left(\frac{c}{w}\right)^2\right]^2 . \tag{7}$$

The procedure for determining $\tilde{C}$ from the load-displacement curve is described in Ref. [14].

Although eq. (4) is strictly applicable only when there is no subcritical crack growth, it has been found experimentally [11] that, even when subcritical crack growth occurs, determination of $\tilde{G}_c$ from the entire load-displacement record up to the initiation of unstable fracture gives good results. The nonlinear energy method has also been applied to cyclic tension-tension loadings in which each load peak exceeded the previous one according to an exponential function [13]. In this work the cyclic nonlinear energy toughness, $\tilde{G}_{fc}$, was not determined from individual load excursions but from an envelope of all cyclic curves prior to unstable fracture. Since the unloading and reloading curves follow essentially the same path, as illustrated in Fig. 2, it is apparent that no major inelastic processes are occurring during this unload-reload cycle. Of course, minor damage accumulation is occurring in each cycle, so the cumulative effect can be incorporated into the envelope of the individual cyclic curves. This procedure was used for a limited number of tests on 2024-T3 and 7075-T6 aluminum alloys. Based on the knowledge gained in the earlier research [13], this procedure is examined further in this report.

EXPERIMENTAL PROCEDURE

In this research program, a number of cyclic loading tests were performed on center-cracked sheets of 7075-T6 aluminum alloy. These specimens were made from 0.063 in. (1.6 mm) thick sheets with the length, L = 30.0 in. (762 mm), gauge length, GL = 27.0 in. (686 mm), width, w = 12.0 in. (305 mm), and crack length-to-width ratio, c/w = 0.5. The notches were made by milling and were subsequently sharpened to a notch-tip radius of 0.003 - 0.005 in. (0.07 - 0.13 mm) with the use of a screw head file. To measure subcritical crack growth, the region ahead of the notch-tip was coated with a thin layer of Dykem layout blue and lines perpendicular to the notch were scribed at an interval of 0.050 in. (1.27 mm). Observations of the crack growth were facilitated by the use of a hand-held magnifier (10x). Using this procedure it was possible to measure crack growth to an accuracy of 0.005 in. (0.13 mm).

The cyclic loads were applied according to the relation

$$F_n = F_o\,(1-e^{-nx})\,, \qquad (8)$$

where F_o = estimated fracture load in monotonic loading,

n = cycle number,

x = increment per cycle, and

F_n = the load corresponding to cycle number n.

Since most of the load cycles for any value of n are applied at the upper range of load levels, their effect on crack-tip plasticity and subcritical crack growth is maximized. Different load increments have been employed through selection of different values of x so that the variation in $\tilde{G}_{fc}$ was obtained as a function of the number of cycles to failure, as was previously done for the 2024-T3 aluminum alloy sheets [13]. The tests were carried out with values of x varying from infinity (monotonic loading) to 0.001. The tests were performed on an MTS machine operated in load control. For each cycle the specimen was loaded in 20 seconds and unloaded in 10 seconds. The load-displacement curves were recorded on an X-Y recorder and the envelope of all of the cyclic curves was used to determine $\tilde{G}_{fc}$.

RESULTS AND DISCUSSION

Decreasing the load increment, x, causes a decrease in the rate of increase in load per cycle, and hence an increase in the number of cycles to failure. The variation of $\tilde{G}_{fc}$ as a function of the number of cycles to failure, N, is seen in Fig. 3. The $\tilde{G}_{fc}$ values corresponding to $N = 1$ $(x=\infty)$ were taken from monotonic loading tests conducted earlier. The values of $\tilde{G}_{fc}$ exhibited a tendency to decrease with increasing cyclic life. As was seen for 2024-T3 [13] the decrease was approximately a linear logarithmic function of the cyclic life in

the initial portion, but the decrease in load in the higher cycle range was faster and started to deviate from a straight line. The curve had the appearance of a compressed S-N curve, with the number of cycles to failure being much smaller than in the unnotched test because the crack initiation phase is suppressed in the notched specimens. The variation in the crack growth behavior with x is illustrated in Fig. 4, where it is seen that the amount of cyclic crack growth increased with decreasing load increment.

It was noted that more scatter appeared in 7075-T6 toughness values than in the 2024-T3 alloy. This was also observed in the static fracture toughness testing of these alloys, and is generally attributed to the increased brittle nature of the 7075-T6 alloy. The specimen which failed after 812 cycles had a much larger toughness than other specimens of the same order of cyclic lifes. The fracture surface of this specimen was unique. Whereas all the other specimens failed with a full slant fracture surface, the fracture surface of this specimen had a double slant face and a square rupture region at the center of the thickness. The higher cyclic toughness of this specimen is attributed to this difference in fracture mode. It was also seen that the rate of decrease in cyclic fracture toughness with increasing cyclic life was greater for 2024-T3 than for 7075-T6 in the range in which both the alloys were tested. This implies that 2024-T3, in the presence of cracks, is more sensitive to fatigue loading

than 7075-T6, and is opposite to the usually held view. However 2024-T3 was tested only in a smaller cycle range than 7075-T6, and further testing would be needed to confirm this observation.

CONCLUSIONS

The nonlinear energy toughness was evaluated as a failure criterion in cyclic loading of 7075-T6 aluminum alloy. The cyclic nonlinear energy toughness, $\tilde{G}_{fc}$ was found to decrease with increasing cyclic life in a manner similar to a compressed classical S-N diagram. This trend is similar to that observed earlier in the 2024-T3 alloy, but the rate of decrease in $\tilde{G}_{fc}$ with increasing cyclic life was lower for the more brittle 7075-T6 than the ductile 2024-T3, which contrasts with the usually held view that the former is more sensitive to fatigue loading than the latter.

LIST OF REFERENCES

[1] Fracture Toughness Evaluation by R Curve Methods, STP 527, Am. Soc. Testing and Materials, 1973.

[2] J. R. Rice, A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. J. Appl. Mech. p. 379, 1968.

[3] J. A. Begley and J. D. Landes, The J Integral as a Fracture Criterion. Fracture Toughness, STP 514, Am. Soc. Testing and Materials, 1972.

[4] A. A. Wells, Unstable Crack Propagation in Metals. Proc. Conf. Crack Propagation, Cranfield, England, p. 210, 1962.

[5] J. D. Landes and J. A. Begley, Test Results From J Integral Studies -- An Attempt to Establish a J_{Ic} Testing Procedure. Fracture Analysis, STP 560, Am. Soc. Testing and Materials, pp. 170-186, 1974.

[6] R. W. Nichols, et al., The Use of Critical COD Techniques for the Selection of Fracture Resistant Materials. Pract. Fract. Mech. for Struct. Steel, Chapman and Hall/UKAEA, Risley, England, 1969.

[7] J. Eftis, D. L. Jones and H. Liebowitz, On Fracture Toughness in the Nonlinear Range. Engrg. Fract. Mech., Vol. 7, pp. 491-504, 1975.

[8] J. Eftis, and H. Liebowitz, On Fracture Toughness Evaluation for Semibrittle Fracture. Engrg. Fract. Mech., Vol. 7, pp. 101-136, 1975.

[9] D. L. Jones, P. K. Poulose and H. Liebowitz, A Comparison of the Effect of Specimen Thickness and Subcritical Crack Growth on Several Nonlinear Fracture Toughness Parameters. Proc. Sec. Int'l. Conf. on Mechanical Behavior of Mat'ls., Boston, pp. 1252-1257, 1976.

[10] H. Liebowitz, D. L. Jones and P. K. Poulose, Development of the Nonlinear Energy Method for Determination of Fracture Toughness Values. Prospects of Fracture Mechanics, ed. by Sih, van Elst and Broek, Noordhoff, pp. 103-123, 1974.

[11] D. L. Jones, P. K. Poulose, J. Eftis and H. Liebowitz. An Investigation of Nonlinear Fracture Toughness in Aluminum Alloys Under Plane Stress Conditions.

[12] H. S. Lamba, The J-Integral Applied to Cyclic Loading. Engrg. Fract. Mech., Vol. 7, pp. 693-703, 1975.

[13] P. K. Poulose, D. L. Jones and H. Liebowitz, Determination of Nonlinear Energy Toughness Value for Cyclic Loading Applications. Engrg. Fract. Mech., Vol. 8, pp. 293-299, 1976.

[14] H. Liebowitz and D. L. Jones, On Test Methods for Nonlinear Fracture Mechanics, Tenth Anniv. Mtg. Soc. Engrg. Sci., Raleigh, NC, 1973.

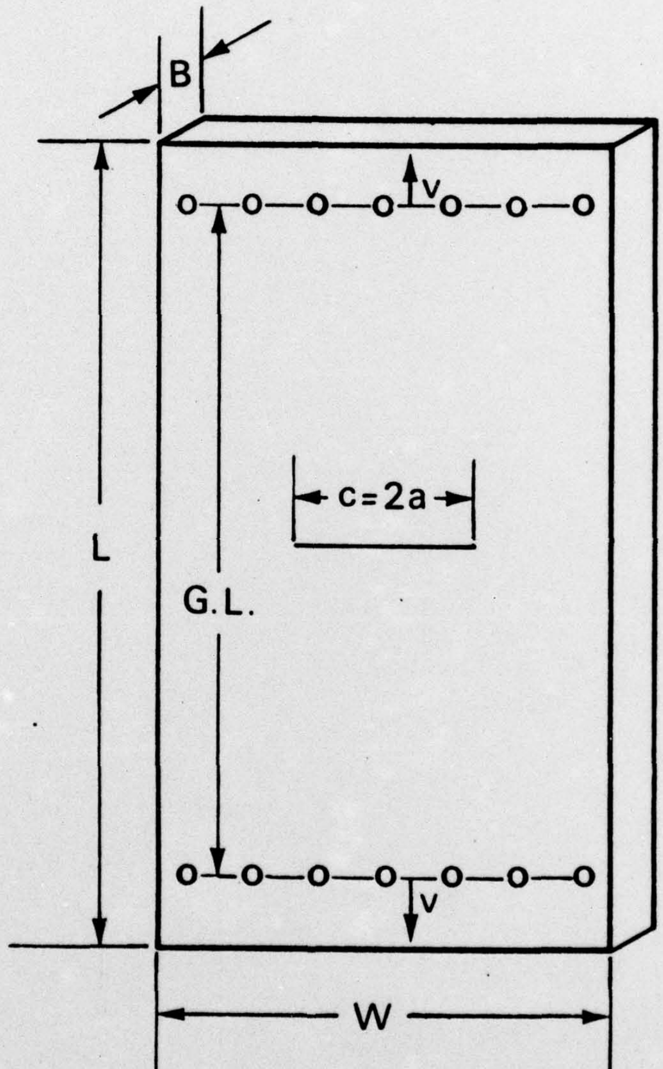

Fig. 1. General specimen geometry

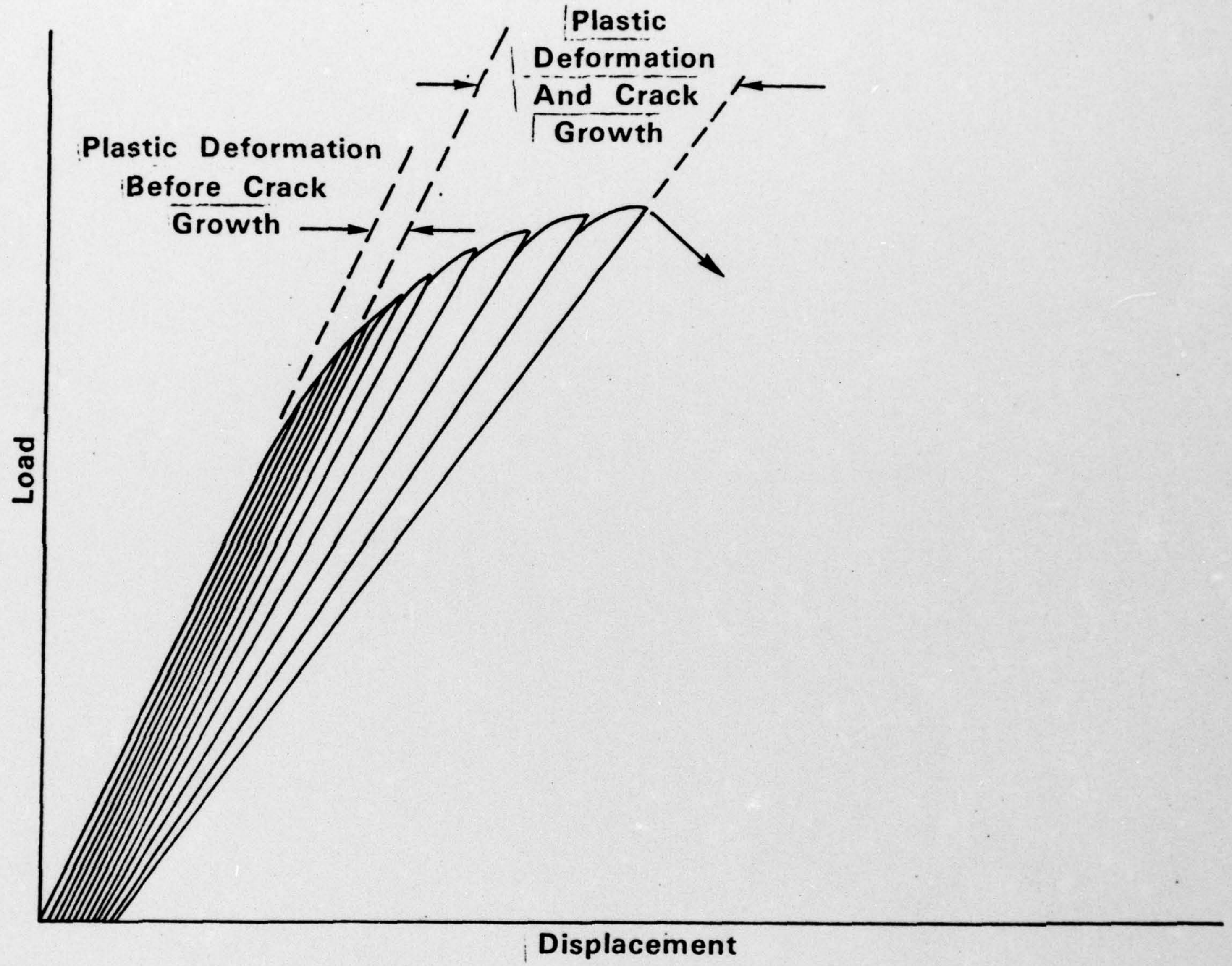

Fig. 2 A schematic representation of load-displacement curves in cyclic loading

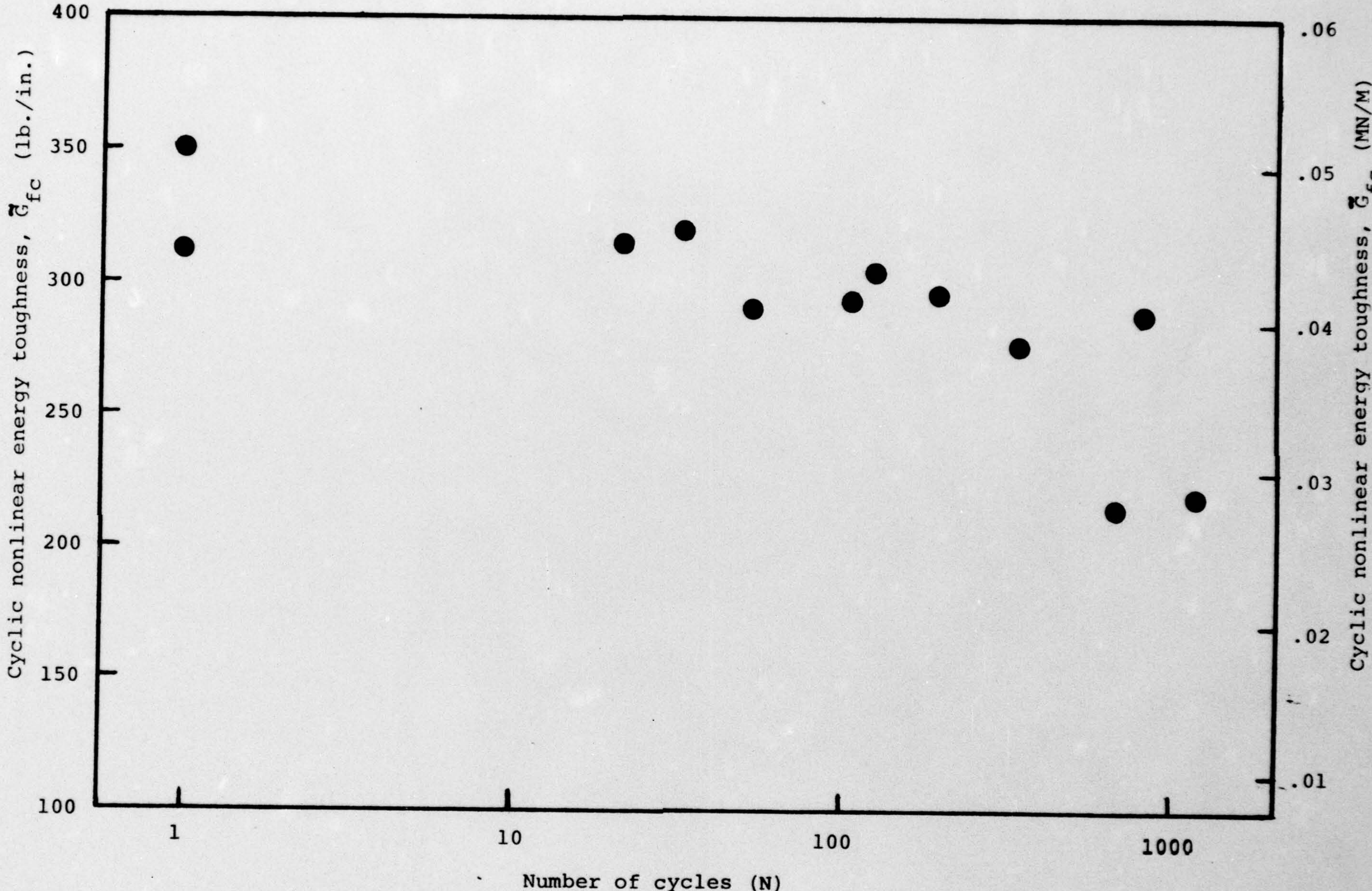

Fig.3. Variation of cyclic nonlinear energy toughness with number of load cycles to failure in 7075-T6 alloy.

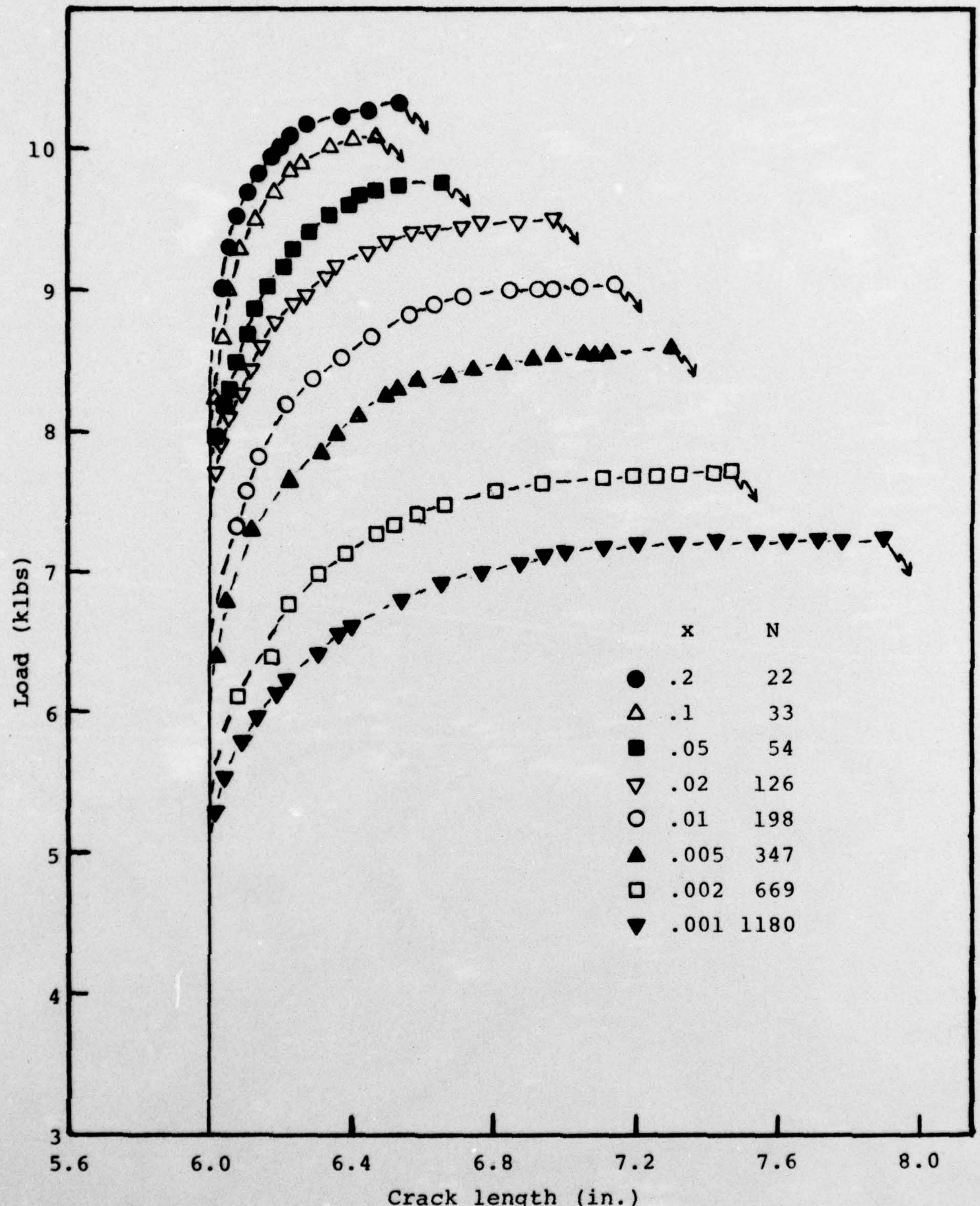

Fig.4. Crack growth curves for different cyclic load increments in 7075-T6 alloy.

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In this report, the nonlinear energy method for fracture toughness determination has been applied to cyclic loading conditions. The nonlinear energy toughness for cyclic loading, $G_{(fc)}$ was obtained from an envelope of the cyclic load-displacement record for thin center-cracked sheet specimens of 7075-T6 aluminum alloy. A cyclic loading program, in which each succeeding load peak approached the static load in an exponential manner, was applied to these specimens. With constant specimen dimensions, different load increments were used for different

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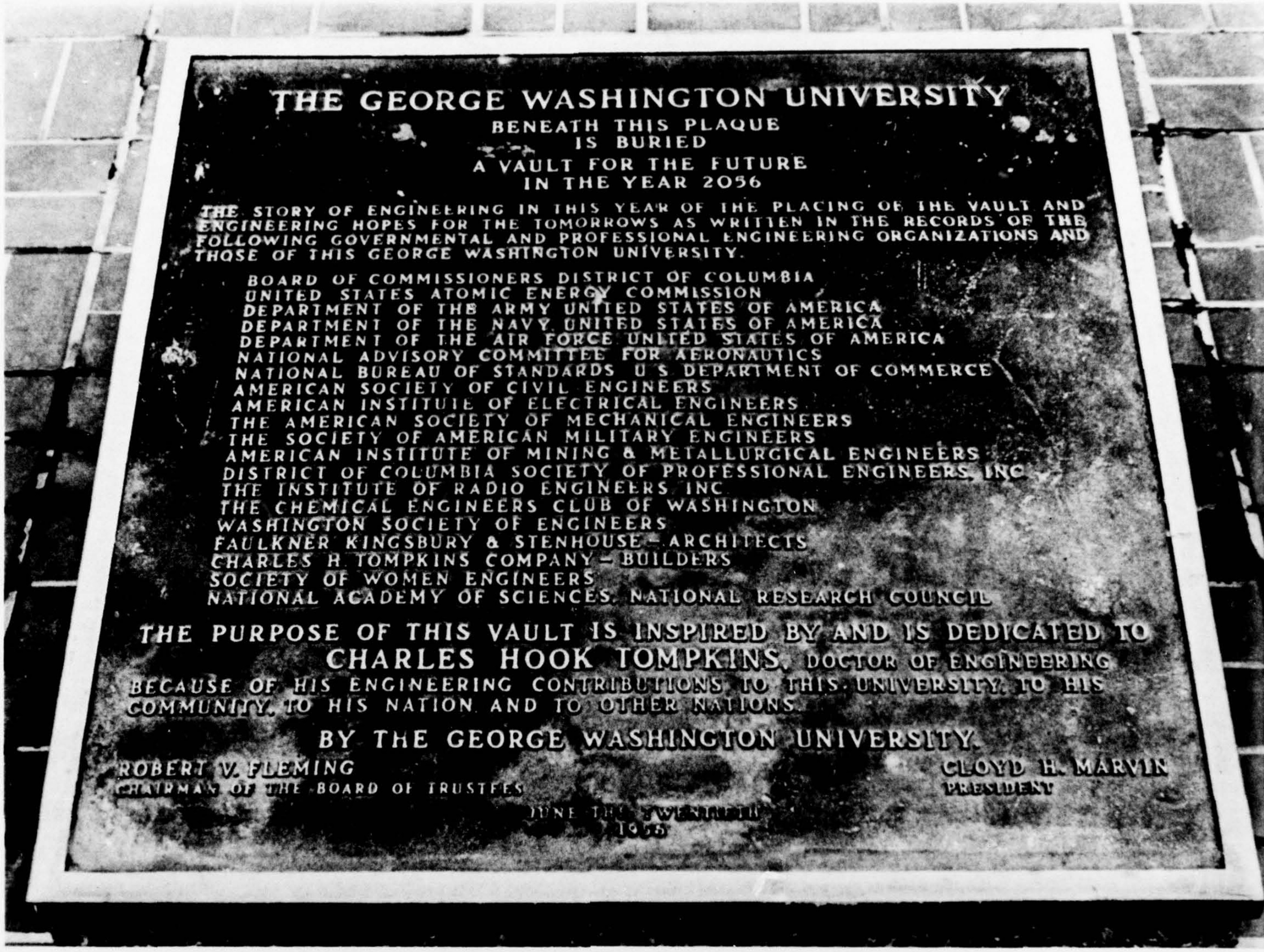

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